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ORIGINAL ARTICLE

Closed coal mine shaft as a source of carbon dioxide emissions

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Abstract The closure of coal mines does not terminate their impact on the environment. Gas emissions into the atmosphere are the one of the problems. The closed "Gliwice II" shaft has been selected for a series of measurements to assess greenhouse gas emissions from the closed mine; however, only CO_2 emission has been detected. The article compromises obtained knowledge about the rate of emissions and the influence of meteorological parameters on this phenomenon—baric tendency, difference in dry-bulb temperature between flowing gas and the atmosphere (buoyancy effect) and wind speed. In the course of the conducted research, it was detected that the highest amount of carbon dioxide emission was $V_{CO_2} = 0.023$ m^3/s (which is 82.8 m^3/h) when baric tendency of pressure drop was 0.57 hPa/h, and the difference between dry-bulb temperatures gas and atmosphere was +4.4 °C (the highest difference in the obtained results). The rate of CO_2 emissions varied from 12.7 to 162.3 $\mathrm{kg}_{CO_2}/\mathrm{h}$. Carbon dioxide was detected up to 43 m from the shaft. The results can be considered as a general conclusion about gas behavior when it flows from the underground sites to the surface in natural conditions and about gas concentrations near a point of emission, especially in the case of former mines. However, it may also be useful for other applications, e.g., the leakages from installations of underground coal gasification, or gas drainage.

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Introduction

The main repercussions of coal mine closure are: land subsidence, rising underground water levels and its further contamination (Suponik and Blanko 2014) and gas migration into the atmosphere (Sułkowski et al. 2008). Carbon dioxide is the most common of all gases in a coal mine. It is also considered as greenhouse gas. CO_2 is the primary anthropogenic greenhouse gas, accounting for 77 % of the human contribution to the greenhouse effect in a recent decade (26–30 % of all CO_2 emissions) (Songolzadeh et al. 2014).

However, apart from environmental issues, gas emissions (including CO_2) from closed mines can also create a local public safety hazard (Creedy 1993; Prokop 2001). Considering abandoned mines and mines which are currently operational, methane emissions are expected to appear, too (Cheng et al. 2011; Ostrowski et al. 2015; Yiwen et al. 2016).

The literature studies indicate that gas can be detected mainly above faults and closed shafts (Annunziatellis et al. 2008; Wrona 2010). The term "closed" refers to a shaft which is temporarily or partly closed, but it can be left "open" for special purposes, e.g., water pumping, which is a common situation in The Upper Silesia Coal Basin (USCB) in Poland. There are 31 such shafts used for this purpose. An "open" shaft has been selected for the examinations ("Gliwice II" shaft).

The second problem is sudden collapse of filling material in an abandoned or closed shaft. Such a situation can be observed even long time after the closure of a shaft, (e.g., after 70 years) (e.g., Wrona 2010). This process, which is caused by underground water eluviations of filling material, can lead to unexpected gas emissions or significant gas hazard at the surface. Similar problems were detected in the UK, Germany, France, China, South Africa, the Czech Republic, Poland etc. (Thieleman et al. 2000; Prokop 2001; Creedy et al. 2003; Hall et al. 2006; Sułkowski et al. 2008; Lagny et al. 2013; Mhlongo and Amponsah-Dacosta 2015).

The problems of gas leakage from underground sites are not only the problem of abandoned coal mines. It is also possible in other operations, e.g., as a result of some break down or emergency situation during gas drainage, during underground coal gasification (UCG) (e.g., Jones and Thune 1982; Lewicki et al. 2007) or during carbon capture and storage (CCS) (e.g., Bateson et al. 2008; Karacan et al. 2011; Labus and Bujok 2011; Moni and Rasse 2013; Paulley et al. 2013). Leakage of CO_2 through plugged and abandoned wellbores is one of the major concerns for long-term safety and effectiveness of geologic CO_2 sequestration (Pawar et al. 2009).

Potential UCG or CCS sites include geologic formations with cap rocks of low permeability to trap CO_2 and prevent migration back into the atmosphere. However, leakage through this caprock via wells or faults and fractures is possible (Esposito and Benson 2011). It can lead to termination of the processes and/or to gas hazard at the surface.

This indicates that the obtained results have an international context and the problem is not limited locally to Poland and not only to underground mining.

The assessment of possible rate of emissions and determination of influencing factors were the base for starting up the research into this matter.

Preliminary surveys at selected shaft showed that there were significant carbon dioxide emissions into the atmosphere. Low concentrations of oxygen have been detected, too. The results obtained during preliminary surveys (February–September 2014) are attached in Table 1.

Apart from other factors, which can be considered as "mining and geology factors" (e.g., gas bearing capacity, geological structure, level of underground water, presence of faults etc.), the process of gas emissions strongly depends on atmospheric pressure changes (Sulkowski and Wrona 2006), and the emissions are noted mainly during pressure drops. Examinations conducted by Sulkowski and Wrona (2006), Wrona (2015) pointed out that the process (gas flux rate) depends more on a baric tendency assigned as TB (TB is a change of pressure in a unit of time computed for three previous hours and in this article is assigned a positive value; however, it is referred to here as a pressure drop) rather than on a momentary pressure value. The difference in temperature between the gas and the atmosphere, expressed in this article as $\Delta t_{\mathrm{d}} = t_{\mathrm{d(gas)}} - t_{\mathrm{d(atm)}}$, leads to the buoyancy effect and is another important factor.

The issues mentioned have been taken into the consideration in response to air protection and public health concerns in the surrounding area. This is especially the case at former-mining sites or above the sites where gas is being produced (UCG), transported (gas drainage) or located (CCS).

The site

The abandoned Gliwice II shaft (Fig. 1) (50°16′38.8″N 18°41′01.2″E/50.277435. 18.683663) [the depth 553.2 m, (−316.5 m below the sea level)] is located at a revitalized (post-coal mining and very urban environment) area of a closed "Gliwice" coal mine.

However, the local "Sośnica–Makoszowy" coal mine, which is currently operational, requires the "Gliwice II" shaft for water pumping purposes. "Gliwice II" was a main shaft of the former "Gliwice" coal mine, and it was closed in 2000.

The abandoned "Gliwice II" shaft is located within the new (modern) industrial area. The site is between the buildings belonging to The Management College in Gliwice (east side) and Future Processing Company (FPark and a kindergarten, west side). The close location of these buildings focuses, on one hand, more attention on safety aspects and, on the other hand, a lack of sprawl in the north and south directions, which produces a sort of unique wind tunnel structure (a kind of trench) for wind direction (mainly from the south). The example of a wind rose for the March measuring period is presented in Fig. 2. It is quite clear that the southern direction of the wind was dominant.

The layout of the shaft which includes a water pumping system is presented in Fig. 3.

Three coal seams with an access to goafs area cross the shaft at three levels: +154.0, −55.9, −152.2 m (according to the sea level).

Table 1 Results of gas concentrations obtained during preliminary measurements

	Gas concentration				Velocity of gas w (m/s)
	O_2 (vol%)	CO_2 (ppm)	CO (ppm)	CH_4 (ppm)	
Range	11.2–20.7	940–29,520	0.0	0.0	0.52–1.5

Fig. 1 Site—Gliwice II shaft which is located in a very urban environment

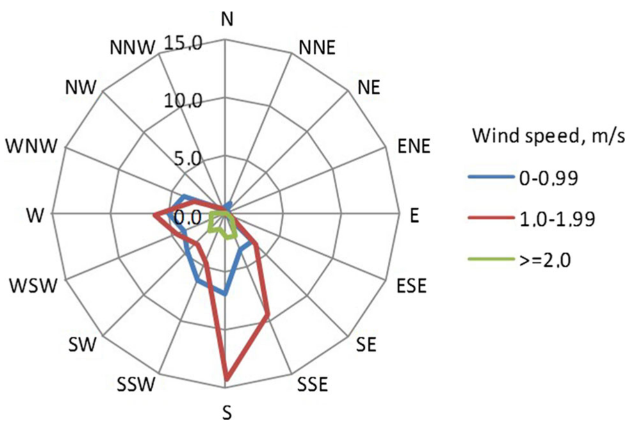


Fig. 2 Wind rose for the March 2014 measuring period

The fan WLE 603A is being turned on for ventilation purposes only when inspection or any other activities in the shaft are required.

Measurements

The measurements were based on good practice methods recommended in the document prepared by the Intergovernmental Panel of Climate Change (IPCC) which is titled "PCC Guidelines for National Greenhouse Gas Inventories, Volume 2 Energy, Chapter—Fugitive emissions" (NGER Act 2009) and on an adequate Polish regulation (PN-Z-04008-02: 1984).

Abandoned underground mines present difficulties in estimating emissions and use of an appropriate method to develop emissions estimates for coal mining in accordance with good practice depends on the quality of data available. The document suggests three methods called "Tiers" (Saghafi 2012). The Tier 1 approach requires a global average range of emission factors and uses country-specific activity data to calculate total emissions. Tier 1 is associated with the highest level of uncertainty. The Tier 2 approach uses average values for the coals being mined. These values are normally developed by each country. The Tier 3 approach uses direct measurements on a mine-specific basis and, if properly applied, has the lowest level of uncertainty (NGER Act 2009).

If mine-specific measurements are available, Tier 3 method should be chosen. In this case, the rate of emission could be determined for the selected shaft by "in situ" measurements.

For the estimation of CO_2 emissions and CO_2 and O_2 concentrations around the shaft, a series of measurements has been undertaken (selected results from the years 2014–2016 are presented in the article). The research has been divided into the following stages:

Preliminary measurements

Due to determination of the range and the rate of emissions, detection of possible gas velocity and gas concentrations were possible. It allowed to select adequate measuring instruments and to determine the measuring lines (grid).

Determination of the measuring lines (grid)

The grid was determined according to proper Polish regulations (PN-EN 15259: 2011). The grid consisted of points along eight lines set according to geographical directions (N, N-E, S, S-E, S, S-W, W, N-W). The grid was with 2 m spacing in the main geographical directions (N, S, E, W) and 3 m spacing in intermediate directions (Fig. 4). The measurements were conducted at the ground level. A gas detector was being moved along the lines with continuous data logging turned on.

Determination of measuring point

According to the wind rose graph (Fig. 2) and the results obtained during preliminary measurements, wind direction was mainly from the south, and the highest concentration of CO_2 was detected along line N. During preliminary series, concentration of $CO_2 = 0.5$ vol% was detected at the distance of 6 m from the shaft (8 m from the outlet), and it was proven by the following series, and selected results are presented in Fig. 5. At a shorter distance, the concentration was higher. The point N-4 (Fig. 4) (6 m from the shaft) was selected for further continuous survey, respectively, to Polish regulations (Regulation 2014) due to CO_2 TLV which equals 0.5 vol%.

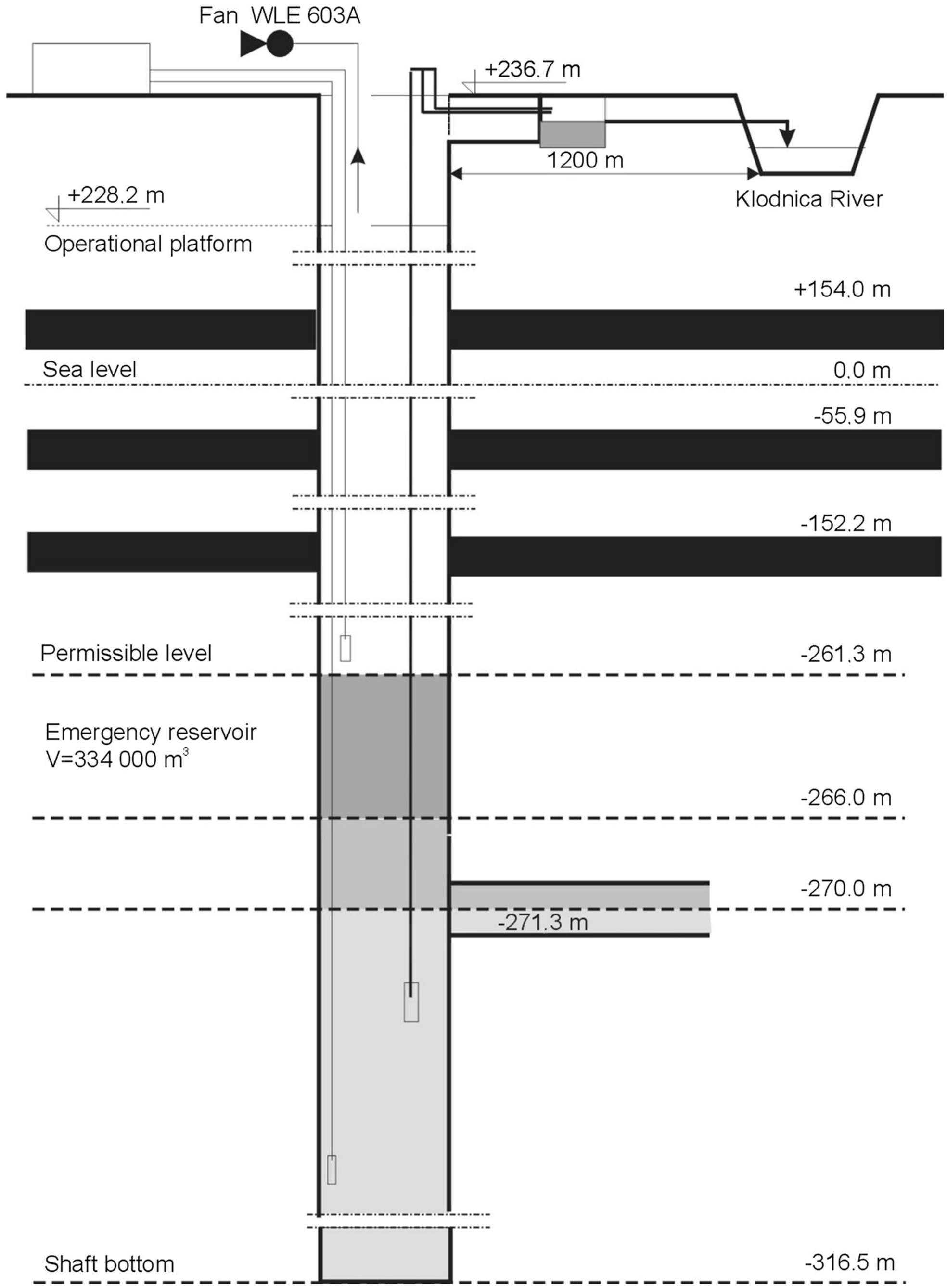


Fig. 3 Layout of the shaft includes a water pumping system

Measurements of meteorological parameters and gas parameters

Atmospheric pressure has been measured and recorded constantly for the baric tendency set. Other parameters for the gases and air (dry-bulb temperature, wet-bulb temperature, velocity) were measured during the tests using Assmann's psychrometer and vane anemometer. In addition, other meteorological data were measured in the immediate vicinity of the shaft with the application of "Atmosphere Parameters Recorder" RPA-1 and multi-functional device "Kestrel 4500". Presented below is a brief specification of the instrument:

RPA-1 specification:
Atmospheric pressure: 800–1300 ± 0.3 hPa
Temperature range: 0 to +50 ± 0.5 °C
Relative humidity range: 5–95 ± 2 %
Measuring interval: $\Delta t = 1$–240 s
Kestrel 4500 specification:
Wind speed range: 0.4…40 m/s,

Fig. 4 Measuring lines (grid)

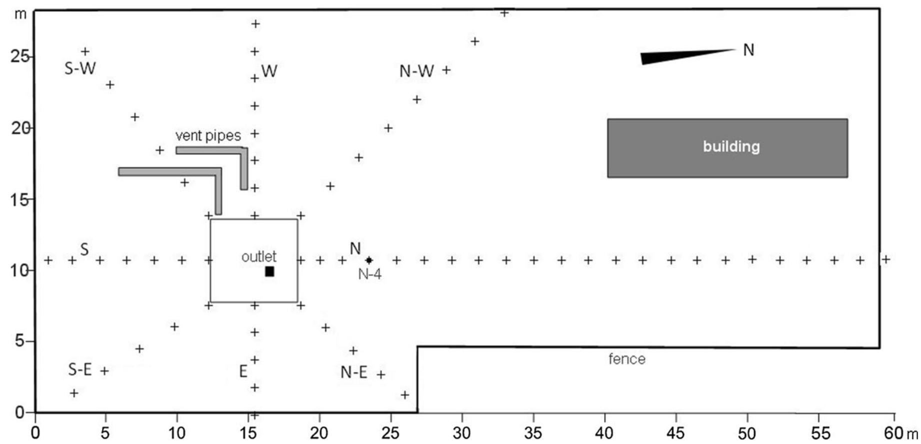
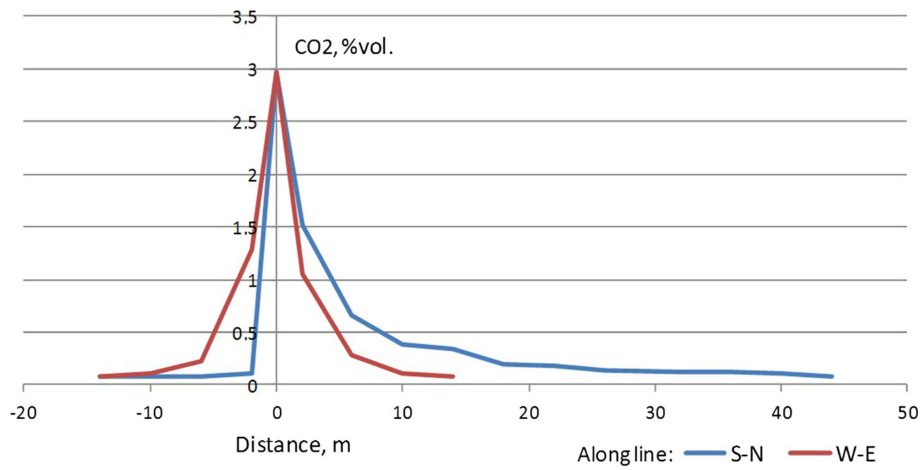


Fig. 5 Comparison of CO_2 concentration along S–N and W-E lines



Wind direction range: 0…360° (measurement uncertainty ±5°).

Estimation of total gas flux rate and CO_2 flux rate

The cover of the shaft includes an outlet of a known cross-sectional area ($A = 0.1564\ m^2$) which allows to perform the anemometer measurements of gas velocity. The rate of gas flux is computed on the basis of multiplication of cross-sectional area and gas velocity (Eq. 1). By knowing the concentration of CO_2 in the mixture, it is possible to calculate the rate of CO_2 flux (Eq. 2).

The estimation of gas flux rate was based on the following formulas (1, 2):

$$\dot{V} = w \cdot A \tag{1}$$

where $\dot{V}$ total volume flow (gas flux rate), m^3/s; w average gas velocity, m/s; A cross-sectional area of the outlet, m^2.

$$\dot{V}_{CO_2} = r_{CO_2} \cdot \dot{V} \tag{2}$$

where $\dot{V}_{CO_2}$, rate of CO_2 emission, $m^3_{CO_2}/s$; r_{CO_2}, CO_2 concentration in total volume flow.

According to IPCC guidelines (NGER Act 2009), the fundamental equation for estimating emissions from abandoned underground coal mines is shown as Eq. (3)

$$\begin{aligned} CO_2\ \text{emissions} &= \dot{V}_{CO_2} - CO_2\text{rec} \\ V_{CO_2\ \text{total}} &= \dot{V}_{CO_2} - V_{CO_2\text{rec}} \end{aligned} \tag{3}$$

where $V_{CO_2\ \text{total}}$ total CO_2 emission rate, $m^3_{CO_2}/s$; $V_{CO_2\text{rec}}$ CO_2 emissions recovered, $m^3_{CO_2}/s$.

In the case of Gliwice II shaft, there is no gas recovery; therefore, Eq. (3) can be transferred in Eq. (4)

$$\begin{aligned} CO_2\ \text{emissions} &= \dot{V}_{CO_2} \\ V_{CO_2\ \text{total}} &= \dot{V}_{CO_2} \end{aligned} \tag{4}$$

Uncertainty assessment

The Tier 3 methodology has lower associated uncertainty than Tiers 1 and 2 because the emissions inventory is based either on direct measurements or on mine-specific information including active emission rates and mine closure dates (NGER Act 2009).

According to (Mutmansky and Wang 2000; NGER Act 2009), spot measurements of gas concentration in ventilation air are probably accurate to ±20 %, depending on the equipment used. Ventilation airflows are usually fairly accurately known (±2 %). When combining the inaccuracies in emissions concentration measurements with the imprecision due to measurement and calculation of instantaneous measurements, the overall emissions for an individual mine may be underrepresented by as much as 10 % or overrepresented by as much as 30 %.

The outlook of applied instruments for the measurements of CO_2 and O_2 concentrations at the outlet of the shaft and at the points of the grid

The measurements were taken by the following devices:

MultiRae IR Plus	CO_2 range 0–50000 ppm (non-dispersive infrared sensor) with resolution 10 ppm, O_2 range 0–30 vol% with resolution 0.1 vol% (electrochemical sensor)
Crowcon Custodian	CH_4 range 0–100 % LEL (electrochemical sensor), CO range 0–500 ppm (electrochemical sensor).

Results and discussion

The results are collected in the following subchapters. They comprise measurements of gas concentrations along N line, at N-4 point, the influence of wind speed on gas concentrations at this point, determination of momentary CO_2 emission rate and a relation between gas flux rate and baric tendency.

CO_2 and O_2 concentrations: the lines

CO_2 and O_2 concentrations have been measured continuously along the lines presented in Fig. 4. During measuring series, it was found that main wind direction (from the south according to the wind rose in Fig. 2) gives main line N for CO_2 emissions.

Comparison of CO_2 and O_2 concentrations along main lines is presented in Figs. 5 and 6.

Change of CO_2 concentration along N line on different days is presented in Fig. 7.

The highest concentration of CO_2 was noticed at the outlet, and then it decreased down to 43 m (series 8) from the shaft where it reached the background value. The change of CO_2 concentration along the N line is described by the lines in the Fig. 6. Except two cases (series 7 and series 8), it can be noticed that the distance 6 m from the shaft indicates the point where CO_2 concentration equals 0.5 vol% or less.

Figure 8 shows change of oxygen concentration along N line for different days. Similarly to CO_2 results, except the same lines (series 7 and series 8), 6 m from the shaft is the point where oxygen concentration equals 20.0 % or more.

N-4 point

Considering N line as main path for air pollution spread (according to wind rose and achieved results) and discussing the change of concentration of CO_2 along this line due to TLV regulations (Regulation 2014), point N-4 was selected for further continuous measurements (it is explained in p.2.2). The results are presented in Fig. 9.

The devices were set at the point N-4 and data logging was turned on at 8:24. On that day, pressure started to fall in the same time. The measurements lasted until 18:18. The pressure changed from 998.8 to 992.2 hPa, and CO_2 concentration started to increase significantly about 14:06. Several peaks of CO_2 concentration can be observed in Fig. 9. The highest recorded value of CO_2 concentration was 1210 ppm at 18:05.

It was noticed that CO_2 detection at N-4 point was not detected at the beginning of the pressure drop, but at 14:06.

It is also important that when wind speed exceeded 0.5 m/s, CO_2 concentration was getting low, up to 600 ppm. Peaks of CO_2 concentration were when wind speed was lower than 0.5 m/s.

However, the change of CO_2 concentration should be compared with wind speed at the measuring point. The results of this comparison are presented in Fig. 10.

Carbon dioxide detection at N-4 point started at 14:06. Looking in the Figs. 10 and 11 (where the diagram is zoomed out to be clearer), the relation between values of wind speed and values of carbon dioxide concentration can be observed.

Figure 11 presents significant momentary peaks of carbon dioxide concentration which equal from 730 to 1290 ppm. Every peak is related to wind speed decrease below 0.5 m/s.

Gas flux rate: the influence of baric tendency and buoyancy

During the measurements, CO_2 emission rate varied between 0.0018 $m^3_{CO_2}/s$ (6.48 $m^3_{CO_2}/h$) and 0.023 $m^3_{CO_2}/s$ (which is 82.8 $m^3_{CO_2}/h$). Assuming CO_2 density to be of 1.96 kg/m^3, it can be stated that CO_2 emission varied from 12.7 to 162.3 kg_{CO_2}/h.

According to present state of the art, apart from "mining and geological" factors, gas emissions from underground

Fig. 6 Comparison of O_2 concentration along S–N and W-E lines

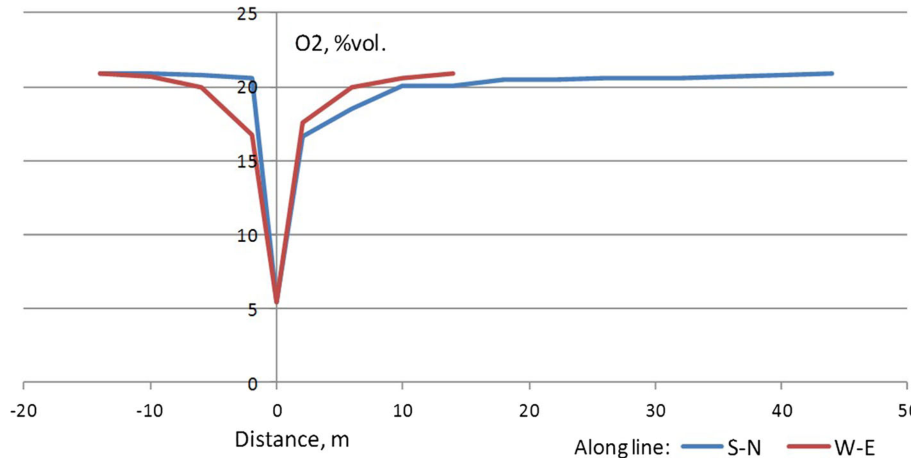


Fig. 7 Change of CO_2 concentration along N line on different series

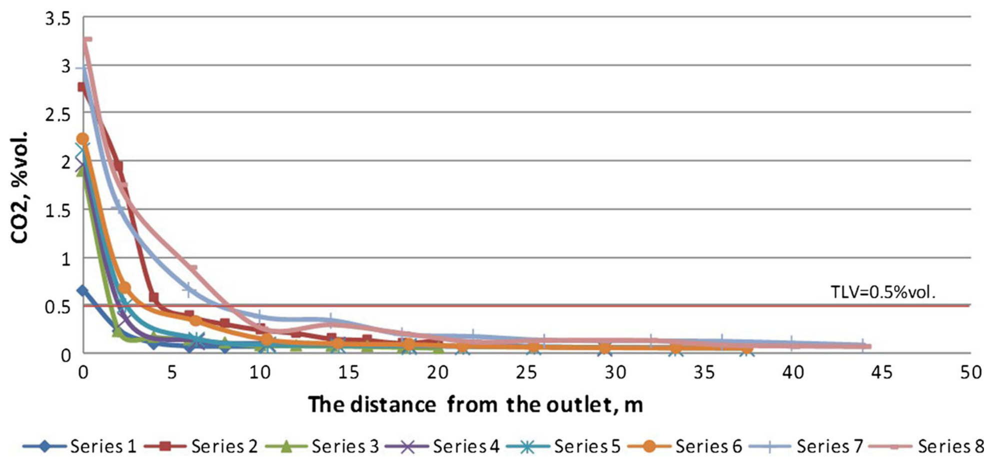
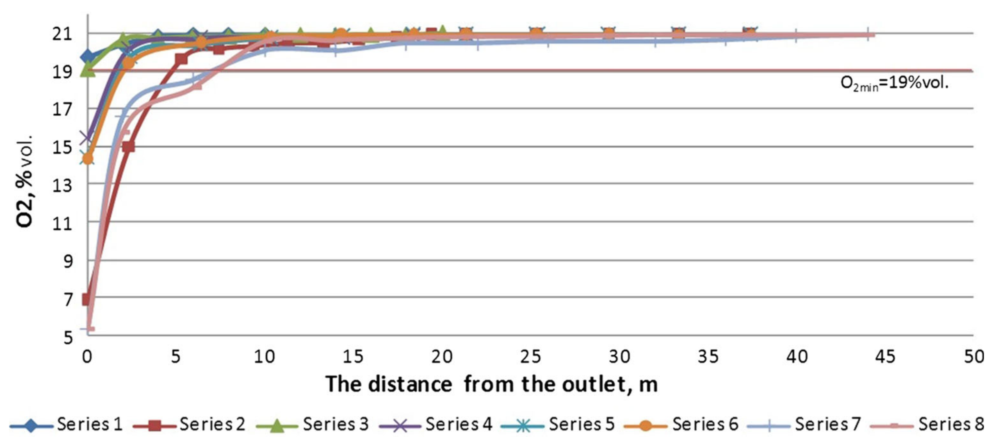


Fig. 8 Change of O_2 concentration along N line on different series



sites are forced by meteorological factors, mainly baric tendency of pressure drop and buoyancy effect (Hikle 1994; Sulkowski and Wrona 2006; Wrona 2015).

Figure 12 shows the results of conducted research into the influence of baric tendency on carbon dioxide emissions from the shaft. It can be observed that rising baric tendency makes carbon dioxide emissions more intense, except values of TB = 0.6 and 0.67 hPa/h. To explain the obtained results, the effect of buoyancy was checked. The findings gave a possibility to determine the principal formulas describing relation between TB V_{CO_2}, V_{gas}, and CO_2 concentration. They are included in Fig. 12.

The results were based on the measurements of dry-bulb temperature of the gas and the atmosphere. The difference between them expressed as Δt_d can accelerate or slow down the process of gas emissions.

Fig. 9 Example of change of CO_2 concentration and pressure at N-4 point

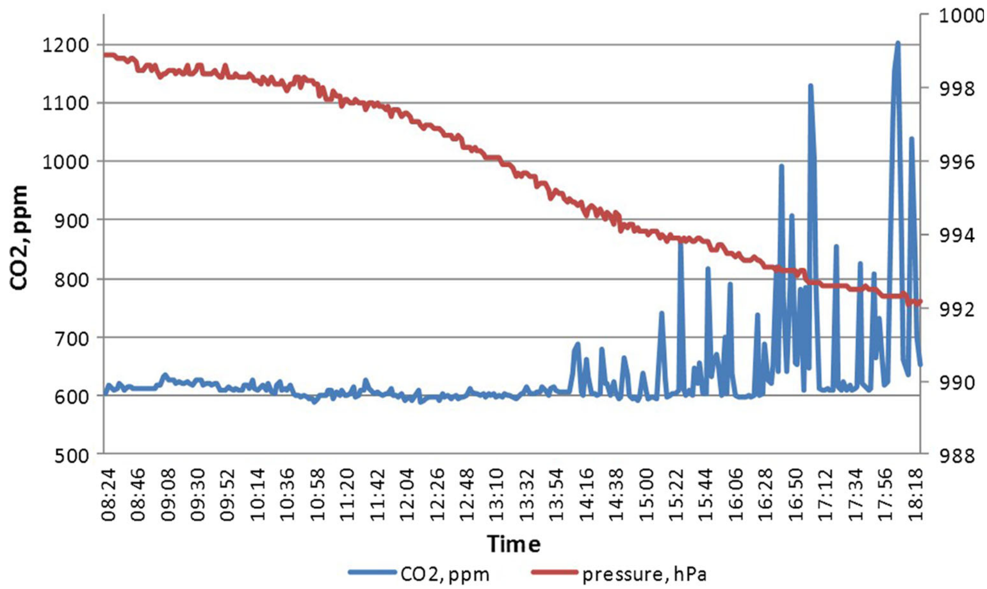
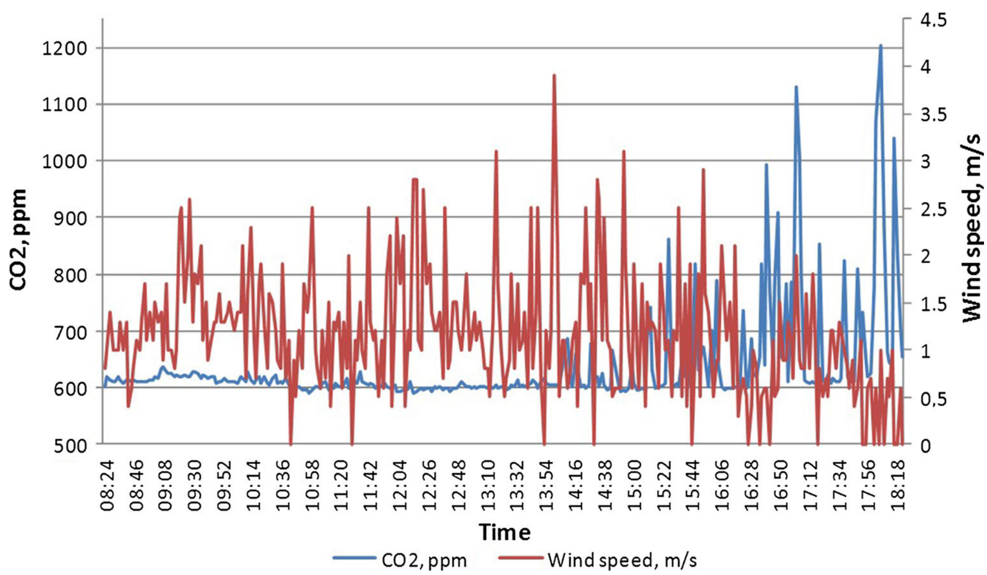


Fig. 10 Change of CO_2 concentration and wind speed at N-4 point



The results are presented in Fig. 13.

Figure 13 shows additional aspect of gas emissions from underground sites—the influence of Δt_d. It results in the buoyancy effect. The relation between Δt_d and V_{CO_2} is included in Fig. 13; however, relatively small value of R^2 gives an information that further research into this matter is required.

Analyzing Figs. 12 and 13, it was found that only on 2 days (when TB = 0.53 hPa/h and TB = 0.57 hPa/h), Δt_d was positive, and it was 1.0 and 4.4 °C (the two points in the right part of Fig. 13). It means that on these days, gas was warmer than the atmosphere, and it led to the acceleration of the process. It explains the highest rate of carbon dioxide emissions noticed in the Fig. 11 when TB = 0.57 hPa/h. In the other cases, Δt_d was negative. It leads to conclusion that the buoyancy effect can accelerate the process, and it should also be considered as an important factor for gas emissions through the shaft.

During the conducted research, it was detected that the highest rate of carbon dioxide emissions $V_{CO_2} = 0.023$ $m^3_{CO_2}/s$ (82.8 $m^3_{CO_2}/h$) was when baric tendency TB = 0.57 hPa/h, and Δt_d was the highest and equaled +4.4 °C.

Discussion

Maximal CO_2 emissions rate from the shaft was 162.3 kg_{CO_2}/h. Assuming 24 h and 365 days for CO_2 outflow, it can be computed that CO_2 emissions could be up to 1421 Mg CO_2/year.

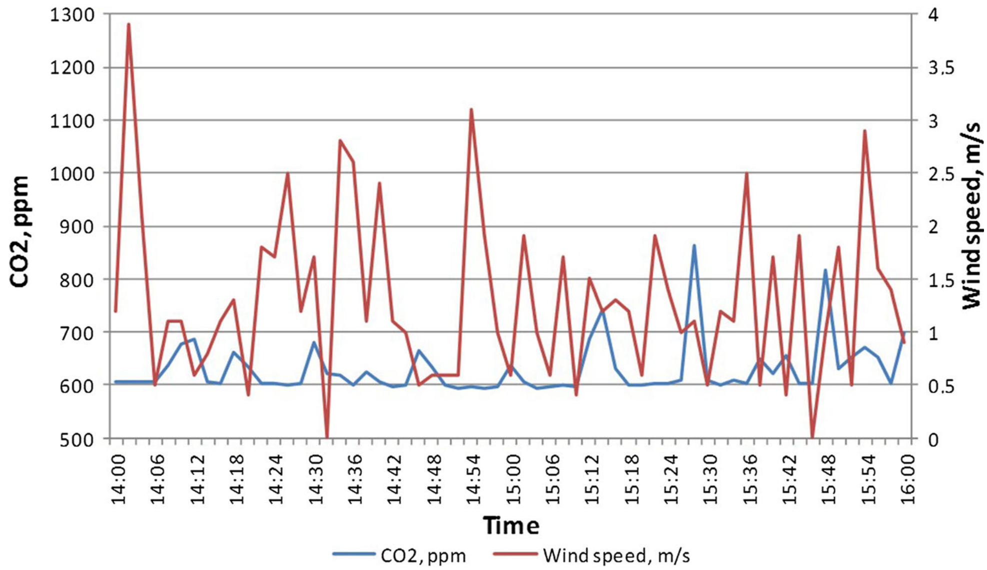


Fig. 11 Selected times—change of CO_2 concentration and wind speed at N-4 point

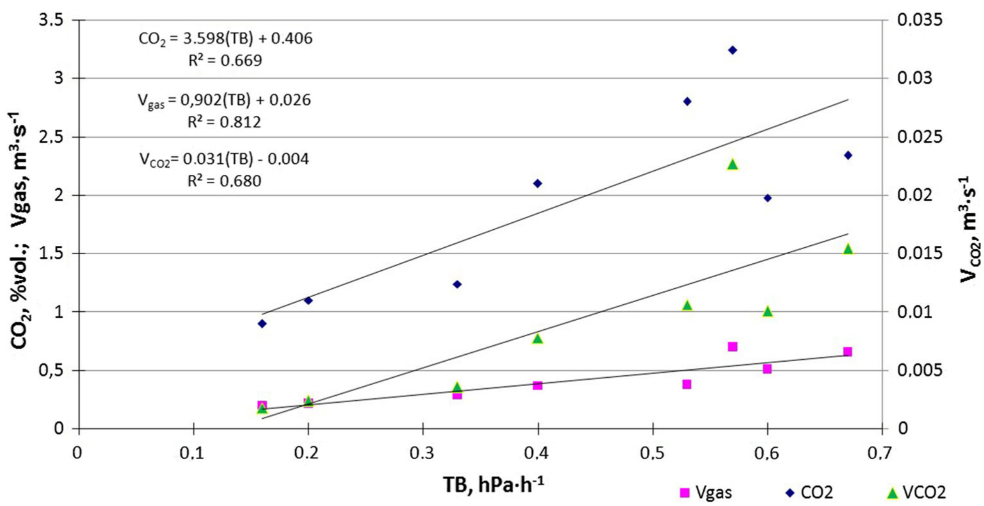


Fig. 12 Change of CO_2 emissions (V_{CO_2}), gas flux (V_{gas}) and CO_2 concentration in the gas according to different baric tendency (TB) for pressure drop

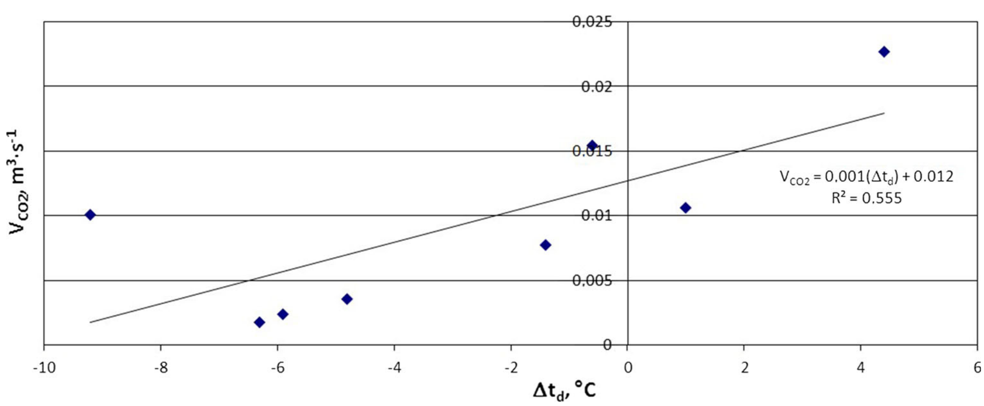


Fig. 13 Influence of difference in dry-bulb temperature between gas and the atmosphere on CO_2 emissions

The result could be compared with other anthropogenic or natural releases, e.g., landfill, mines in operation, road transport or combustion processes.

Considering gas emissions from burning coal waste dumps, it was measured that CO_2 emissions from 1 m^2 of a dump with intense fire were 8375 kg CO_2/year (Różański et al. 2015).

Carbon dioxide emissions by a shaft of an operational mine are 39770 Mg CO_2/year (Zgadzaj 1997). Therefore, the obtained rate of emissions is about 3.57 %, (comparing to operational mine); however, as it was mentioned in the introduction, there are 31 sites of this type in Poland, so total emissions should be larger, and currently, it is the scope of research.

Total CO_2 emissions generated as a result of heating a typical house (based on annual consumption of 20,000 kWh) are for: oil—6.26 Mg/year, natural gas—4.23 Mg/year, wood heating (oven dry)—0.1 Mg/year (Report of Forestry Commission, England).

Consequently, 14,210 houses should be wood heated during a year to obtain the same emission rate as from an abandoned shaft (1421 Mg of CO_2 for year).

Considering the significant rate of CO_2 emissions from a closed shaft and related air pollutions and gas hazard at the surface, this process should be monitored, reported and reduced. Sealing is the simplest one, and it gives positive effects. However, dump bailing of cement may not provide complete effective seals, which was proved by e.g., White (White et al. 1992).

Therefore, there are other methods of controlling the emissions, e.g., special outlet chimney above a shaft allowing the gases to flow to the atmosphere at a higher level above the ground.

Considering reduction of CO_2 emissions, there are several known methods such as: absorption, physical and chemical solvents, physical and chemical adsorption, cryogenic distillation, membrane separation, novel CO_2 capture technologies (Songolzadeh et al. 2014). In addition, CO_2 separation can be related to recycling carbon dioxide into concrete (Shao et al. 2010) or amine-functionalized multi-walled carbon nanotube (Khalili et al. 2013).

Selection of a proper method (considering technical and economical aspects) to the processes of gas emissions from closed mining shafts requires further research.

Conclusions

"Gliwice II shaft" was selected to determine greenhouse gas emissions rate; however, only CO_2 emissions were detected. Nevertheless, the literature studies indicate that during gas emissions from a closed shaft, gas concentrations in the mixture can vary. It depends on the geological factors of a particular site.

Over the 3 years of measurements, the rate of CO_2 emissions varied from 12.7 to 162.3 kg_{CO_2}/h. Maximal detected concentration of CO_2 in gas mixture was 3.24 vol%, and minimal concentration of O_2 was then 5.4 vol%.

The rate of emissions depends on baric tendency (TB) and the difference between dry-bulb temperature of a gas and of the atmosphere (Δt_d), which represents the buoyancy effect. The highest rate of CO_2 emission was $V_{CO_2} = 0.023\ m^3_{CO_2}/s$ (which was 82.8 $m^3_{CO_2}/h$) when baric tendency of pressure drop was TB = 0.57 hPa/h, and the difference between dry-bulb temperatures gas–atmosphere was the highest (of all the series) and equaled +4.4 °C.

Considering CO_2 concentration around the source of emissions (the shaft), the wind direction and wind speed are important. Carbon dioxide was detected in the vicinity of the closed coal mine shaft at the distance of up to 43 m (at the ground level). It was in the northern direction (according to the wind rose).

Continuous measurements conducted at the point (N-4) located at the northern line (N) indicated that momentary peaks of CO_2 concentration are mostly at the same time as the decrease in wind speed.

Considering the Polish regulation due to TLV level for $CO_2 = 0.5$ vol% at a work stand, it can be stated that a special safe zone should be created around the shaft. In this case, concentration of $CO_2 = 0.5$ vol% was detected at the distance of 8 m from the outlet or closer.

The periods of pressure drop with a high value of TB can contribute to an increase in greenhouse gas emissions from the shaft and local gas hazard near the shaft (or any other source of gas emissions from underground sites e.g., gas drainage, UCG processes) especially when Δt_d (gas atmosphere) is positive.

Considering obtained results and related air pollutions and gas hazard at the surface, this process should be monitored, reported and reduced; however, selection of a proper method requires further research.

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